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**DESIGN CRITERIA FOR
A SMALL ANIMAL MAGNETIC-FIELD EXPOSURE FACILITY**

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1. INTRODUCTION

The exposure of small animals to specified physical or chemical agents is an accepted method for assessing the biological activity of the agents, and this method is being used by quite a few laboratories to test for possible biological effects from low-level electric and magnetic fields. However, experiments of this kind are currently very controversial at least partly for the following reasons; first, because the extrapolation from small animals to humans is extremely tentative and, second, because the electric and magnetic field dosimetry is often poorly done.

Biological effects from low-level fields, if they exist, are very weak. It is particularly important, therefore, that the apparatus used to produce the electric or magnetic fields should produce exactly the required fields and should not in any other way influence either the environment or the experimental outcome. This objective is surprisingly difficult to achieve and failure to design and test to rigorous standards should be (but seldom is) grounds for automatic invalidation of experimental findings.

An experiment to test for effects of video display unit (VDU) type radiofrequency magnetic fields and 60-Hz magnetic fields on small animals is currently being proposed by Ontario Hydro jointly with the University of Toronto. In order to assist in the preparation of cost estimates for the experiment, this report examines some of the design criteria for a suitable magnetic-field exposure facility.

2. GENERAL EXPOSURE-FACILITY REQUIREMENTS

The purpose of a small animal magnetic-field exposure facility is to create precisely the magnetic environment that is required to test a biological effects hypothesis according to an agreed experimental protocol, while not interfering in any other way with the normal environment or handling of the laboratory animals.

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The experimental protocol will determine the number and type of animals to be exposed and therefore the size of the facility. It will also determine the exposure parameters such as the strength, time variation, uniformity, and polarization of the field, the duration of the exposures, and the permissible limits on cofactors that may influence the outcome of the experiment such as ambient electric and magnetic fields in the laboratory, heat, vibration, and so on. If some cofactors cannot be adequately limited, then the protocol should allow for the use of a sham-exposed group of animals under controlled conditions in order to cancel out their effects.

An exposure facility should allow the experiments to be conducted "blind". That is, the animal handlers and research personnel should not be able to distinguish between the exposed and sham-exposed or control groups. The preferred method is the use of identical exposure apparatus for both the exposed and sham-exposed groups and the elimination of clues that might identify the active apparatus.

3. PROTOCOL FOR THE ONTARIO HYDRO EXPERIMENTS

Reviews of experimental protocol with Health and Safety Division have established the following partial requirements for a magnetic field exposure facility. These have been used for design purposes although it is understood that they are preliminary and are subject to change.

- The animals will be MusDomestica Cd-3 mice. The mice, space for the facility, handling, and analysis will be provided by the University of Toronto.
- The exposed and sham-exposed groups will consist of up to 50 animals each.
- Exposure to sinusoidal 60 Hz magnetic fields with amplitude up to 1 mT rms is required.
- Exposure to sawtooth type 17 kHz magnetic fields similar to those produced by VDUs with amplitude up to 10 μ T peak-to-peak is required.
- The fields will be linearly polarized in a horizontal plane.
- Exposures will be essentially continuous for up to 20 days except for periods of servicing.

4. DESIGN OF EXPOSURE APPARATUS

4.1 Proposed Configuration.

To meet the above requirements we propose the use of two identical large free-standing Helmholtz coils, one for the exposed group of animals and one for the sham-exposed group, with both coils wired through a "blind" switch to an appropriate power source. The general arrangement is shown in Figure 1.

The advantages of the large free-standing coils are: (a) they will provide a uniform field over the volume occupied by up to 54 mice in their normal laboratory enclosures, (b) little heat or vibration will be transmitted to the animal enclosures, (c) electric fields from the

exposure facility can be kept to very low values and, (d) access to the animals, ventilation, and movement of the animal enclosures are essentially unrestricted.

The disadvantages are: (a) more laboratory space is required both from the physical size of the coils and from the more extensive fringing fields and (b) metallic parts of the existing animal enclosures will have to be replaced with equivalent nonmetallic parts.

The physical and electrical design criteria for this apparatus are described below.

4.2 Physical Design Criteria.

Physical design parameters include the size of the coils, the shape of the coils (circular or square), and the required spacing between the exposed and sham-exposed groups. These are determined respectively by the required uniformity of the field over the space occupied by the animals, the space available in the laboratory, and the upper limit of the exposure allowed to the sham-exposed group.

Field homogeneity and fringing fields are evaluated for circular and square coils in Appendix I. This evaluation shows that using the normal animal enclosures, and without special handling, up to 54 animals can be exposed with a field amplitude variation of +/- 5% in a 1.2 m (nominally 4 ft) per side square coil or a 1.4 m (nominally 4 ft, 6 in) diameter circular coil. The square coil therefore will occupy somewhat less laboratory space and in addition may be somewhat easier to manufacture.

The fringing field from the active coil will be lowest if the sham-exposed group is located in the plane of the coils. At a distance of 3 m, the fringing field will be up to 0.08 μ T with the VDU type field and up to 8 μ T with the 60 Hz field. The latter field is significantly above normal laboratory ambient fields, indicating that the 60 Hz experiments may require a separation of 6 m or more between the exposed and sham-exposed groups.

4.3 Electrical Design Criteria, VDU Fields

The electrical design criteria for VDU fields are developed first as they are considered to be more critical than those for the 60 Hz fields.

The procedure proposed for generating sawtooth type 17 kHz magnetic fields is extremely simple. It is to use the coil itself to integrate an appropriately timed voltage pulse from a conventional pulse generator. This procedure was tested in the laboratory, as described in appendix II, using a standard pulse generator and professional-quality stereo audio amplifier with excellent results.

From appendix II, the pulse generator with or without amplifier must be capable of providing a peak voltage V_p and a peak-to-peak AC current I_{p-p} given by the following formulas:

$$V_p = 2.35 R^2 N H_{p-p}$$

$$I_{p-p} = 1.17 R N^{-1} H_{p-p}$$

where R is the distance between the two halves of the coil, N is the number of turns for each half of the coil, and H_{p-p} is the required peak-to-peak magnetic field in μ T. The minimum values of N and V_{p-p} given a square coil with R=0.6 m, and a pulse generator with an output impedance of 50 ohms, are 22 turns and 186 V respectively. A good match for readily available wideband stereo amplifiers, assuming that one of these is used to boost the output of a conventional pulse generator, is obtained with N about 3 or 4 turns. This

low-impedance combination ensures that a very "clean" waveform is produced and also minimizes the voltage across the coil. The low voltage, in combination with electrostatic shielding of the coil winding if required, will effectively eliminate any electric fields produced by the coil in the working space. With the coil design parameters proposed, a stereo amplifier output power of about 50 W is required for a peak to peak field of 10 μ T.

4.4 Electrical Design Criteria, 60 Hz Fields

The following calculations are based on a coil design consisting of a square Helmholtz coil measuring 1.2 m per side (0.6 m separation) with 4 turns in each coil segment. Assuming that resistive and reactive impedances are equal at 60 Hz, it is shown in appendix III that the same coil will produce a 60 Hz field of 1 mT with a current of 176 A rms and a voltage of 9.4 V rms for a total rating of 1650 VA. A good match is provided by a standard 120 V/12 V, 2 kVA isolation transformer from Hammond Manufacturing Company of Guelph.

To meet the impedance condition, the minimum conductor size is 0.2 cm² or about AWG #4 wire. Water cooling will be required to remove about 1200 W and prevent excessive heating. The electrical and mechanical construction of the coils should not permit any detectable vibration at full current.

5. COST ESTIMATES

The following cost estimates are based on the design criteria developed in this report and are provisional. The major expenses thought to be involved in setting up a magnetic field exposure facility are included, even where cost estimates are not available (NA), as an aid in planning. Although we believe that the equipment costs are reasonably accurate based on current prices, we recommend that the assumptions explicit or implied in these estimates be reviewed with experienced biological effects researchers before major program commitments are made.

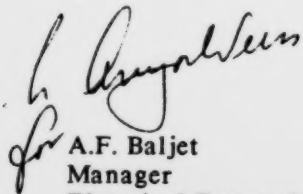
Item 1. Build and test two Helmholtz coils	\$20,000
Item 2. Electrical apparatus for VDU fields	5,000
Item 3. Electrical apparatus for 60 Hz fields	1,000
Item 4. Assemble exposure apparatus	4,000
Item 5. Provide lab space (min 8 m)	NA
Item 6. Limit ambient fields	NA
Item 7. Provide power and water	NA
Item 9. Provide nonmetallic substitutes	NA
Item 10. monitoring and control equipment	NA

6. CONCLUSIONS

The design criteria for a small animal magnetic-field exposure facility have been reviewed with reference to a preliminary experimental protocol. The recommended design for the magnetic field generating apparatus consists of two identical free-standing Helmholtz coils connected to a "blind" switch so that laboratory personnel will not know which one is active. Square coils, measuring 1.2 m to a side and 0.6 m along the axis, will provide a field uniformity of $\pm 5\%$ over the exposed animals. The coils may have to be separated by 6 m or more to avoid fringing field effects.

Calculations supported by laboratory tests show that the required magnetic fields can be produced with moderately priced commercially available current sources. The cost of a fully assembled and tested exposure apparatus is estimated at \$30,000. Other costs will be involved in completing an operational exposure facility but these are not estimated at the present time because of insufficient data.

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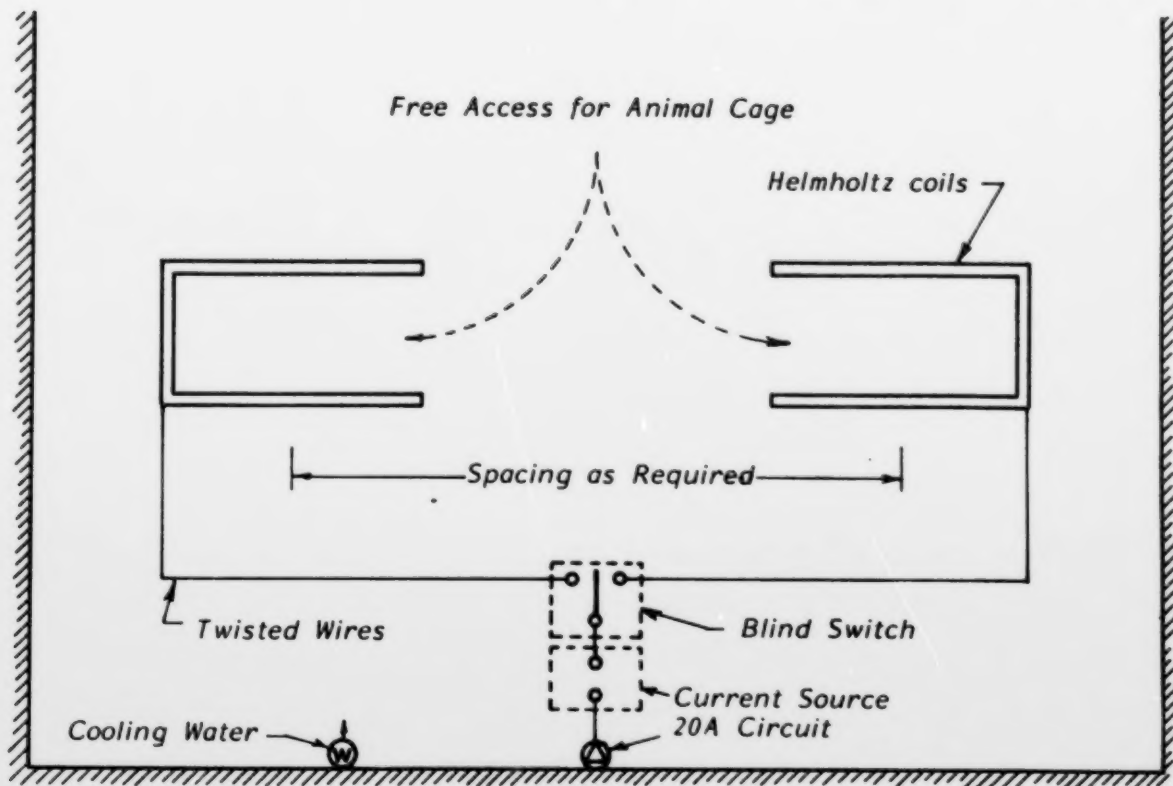


FIGURE 1
CONCEPTUAL LAYOUT OF EXPOSURE FACILITY

APPENDIX I
PHYSICAL DESIGN CRITERIA

The enclosures used at the University of Toronto for Cd-3 mice are open-top plastic boxes about 20 cm wide, 20 cm high, and 30 cm deep. Each box normally has a metal grill placed on top and holds six mice. The boxes are stacked on a wheeled dolly as shown in Figure I.1. Nine boxes holding up to 54 mice therefore occupy a volume of about 60 cm high, 60 cm wide, and 30 cm deep.

This volume fits conveniently into the working field region of a standard horizontal-axis Helmholtz coil. A Helmholtz coil consists of two co-axial coil windings separated by a distance equal to the winding radius if the coil is circular or equal to one half of the dimension of one side of the winding if the coil is square. For proper operation, the windings must be identical and carry identical current. The size of coil needed to yield a field of specified uniformity over this volume may be calculated from formulas given in NBS Technical Note 1191, "Electrical Parameters in 60 Hz Biological Exposure Systems and their Measurement: A Primer". These formulas have been incorporated into a computer program called "coils" for an HP 9826 computer. The formula supplied for circular coils is not very accurate and more precise data for points inside a circular coil have been supplied by Dr. M. Stuchly of the Radiation Protection Bureau in Ottawa.

Figure I.2 shows the range of field values produced over the specified volume by a square coil measuring 1.2 m per side and a circular coil of 1.4 m diameter. Either of these coils will produce a field over the volume that is uniform to within +/- 5%.

Fringing fields produced by a 1.2 m square coil along the coil axis and at right angles to the axis are shown in Figure I.3. The strength of these fields will determine the physical separation between exposed and sham-exposed animal groups. At 3 m, the fringing field is between .8 and 1.5 % of the field at the center of the coil and will change approximately as the inverse cube of the distance.

The proposed physical design for a free-standing Helmholtz coil is shown in Figure I.4. This design is quite non-intrusive and should not affect the normal handling of the animals. However, because of the high field strengths and high frequencies required, ferrous and non-ferrous metal parts should be excluded from the vicinity of the coil.

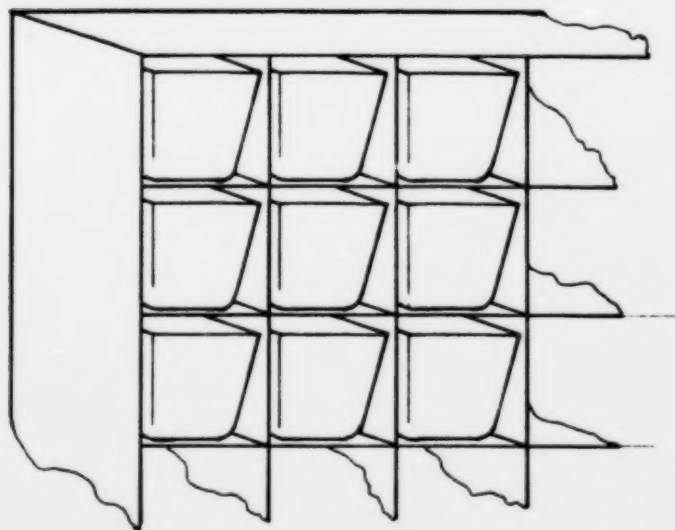


FIGURE 1.1
ARRANGEMENT OF ANIMAL ENCLOSURES

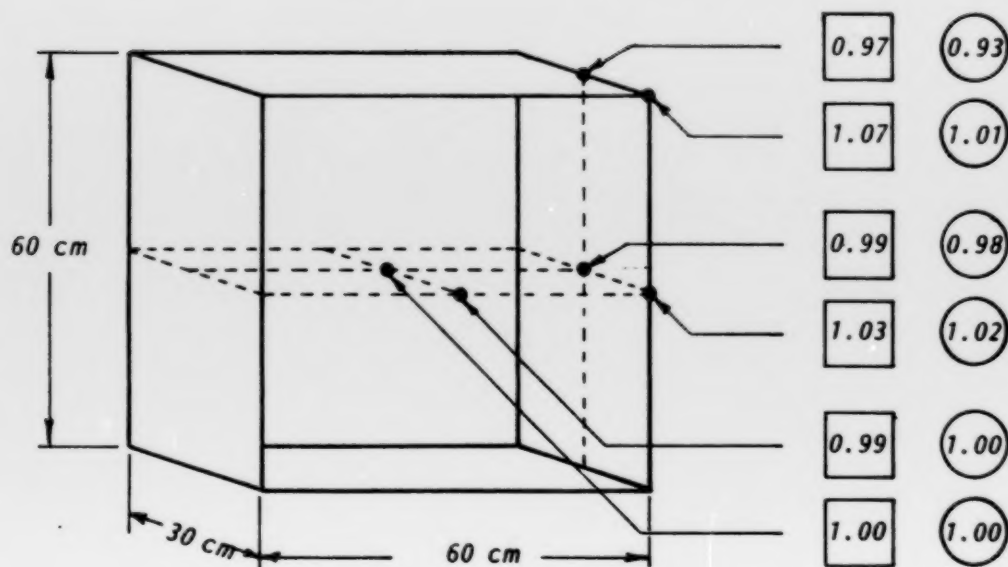


FIGURE 1.2
RELATIVE FIELD VALUES. SQUARE BOXES ARE FOR 1.2 m SQUARE COIL
CIRCULAR BOXES ARE FOR 1.4 m CIRCULAR COIL

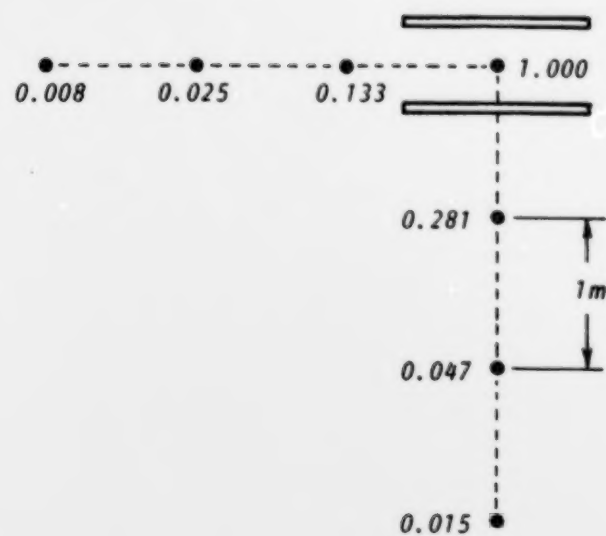


FIGURE 1.3
FRINGING FIELDS FROM SQUARE COIL

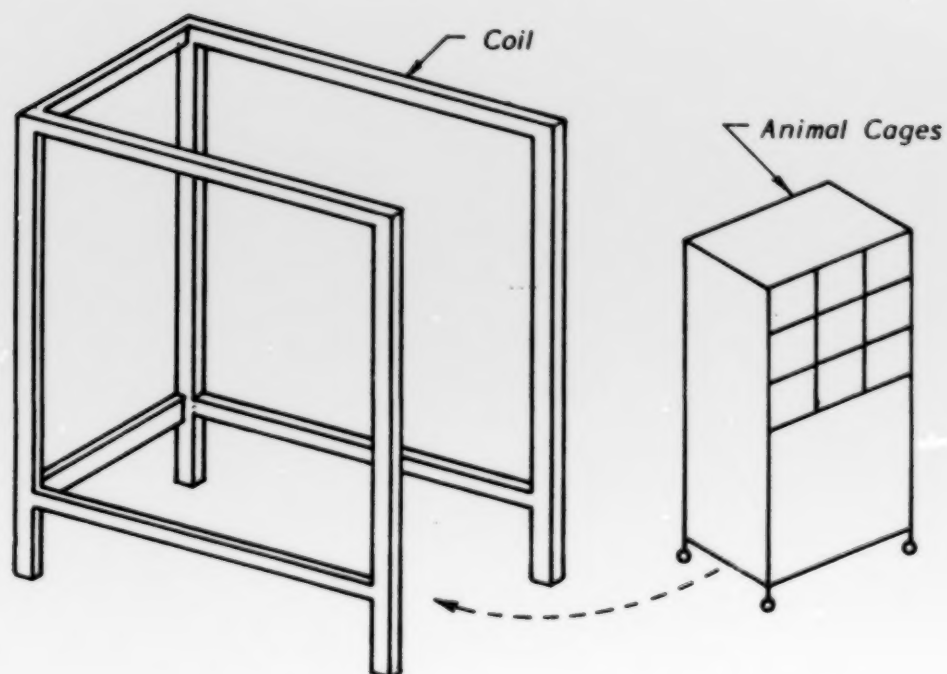


FIGURE 1.4
FREE-STANDING COIL

APPENDIX II

ELECTRICAL DESIGN CRITERIA: VDU FIELDS

Fields of arbitrary waveform may be generated by using a custom designed current generator that produces a current of the correct waveform. In the case of sawtooth type VDU waveforms, a simpler approach is possible using a standard pulse generator. In this approach, the pulse generator is connected directly across the coil and the ratio of the coil inductance (L) to the circuit resistance (r) is adjusted so that the coil current is the integral of the source voltage. The equivalent circuit and its electrical response are shown in Figure II.1.

For VDU fields, the condition is that L/r be roughly equal to or greater than T_1 . Then,

$$V_p = L I_{p-p} / T_1$$

For Helmholtz coils, the inductance L is approximately,

$$L = 10 R N^2 (\mu H)$$

where R is the distance between the coil halves and N is the number of turns on each half of the coil.

The field at the center of the Helmholtz coil is,

$$H_{p-p} = K N I_{p-p} / R (\mu T)$$

where K is 0.90 for circular coils and 0.85 for square coils. Thus for square coils, $T_1 = 55 \mu s$, $T_2 = 5 \mu s$, and H_{p-p} measured in μT ,

$$V_p = 2.35 R^2 N H_{p-p}$$

$$I_{p-p} = 1.17 R N^{-1} H_{p-p}$$

and $r \leq 0.18 R N^2$.

These formulas show that the coil and the pulse source must be matched fairly closely for optimum performance. In particular, a low-voltage source, as required for low values of electric field in the working volume, requires a small number of turns and consequently a very low source impedance (eg around 1 or 2 ohms).

High-power pulse generators are available from several manufacturers, although a special order may be required for the correct specifications. Alternatively, a standard 50-ohm pulse generator may be used with an off-the-shelf stereo-system audio amplifier, some of the better quality amplifiers having almost ideal electrical characteristics for use with low-impedance coils.

APPENDIX II (Cont'd)

The latter procedure was tested with a set of laboratory Helmholtz coils and an Interstate model P25 5-V, 50-ohm pulse generator connected to a Yamaha model PC5002M amplifier. The coil parameters are: $L = 600 \mu\text{H}$, $R = 0.5 \text{ m}$, $N = 11$, and coil resistance $r_c = 0.5 \text{ ohms}$. The amplifier is rated at 500 W per channel with a power bandwidth of 100 kHz. Only one channel was used. The pulse generator was set to produce a 5 μs pulse at a pulse repetition rate of 17 kHz.

The voltage produced across the coil and the field waveform measured at the center of the coil are shown in Figure II.2. The maximum peak pulse voltage available from one channel of the amplifier is 120 V and the corresponding peak-to-peak magnetic field at the center of the Helmholtz coil is 21 μT . These values and the actual field waveform are in excellent agreement with theory. In addition, the calculations show that the amplifier is actually operating substantially below its current capacity and that the field can therefore be increased further by decreasing the number of turns on the coil. The actual limit is not known because the output resistance of the amplifier is unspecified, but a reasonable estimate is that the maximum field will be reached at about 3 or 4 turns.

This experiment proves that the proposed procedure is quite practical. By scaling, a peak-to-peak field of 10 μT should be obtained at the center of the recommended coil with 4 turns, a peak pulse voltage of 34 V and a peak-to-peak current of 1.8 A. The required amplifier power rating will be about 50 W.

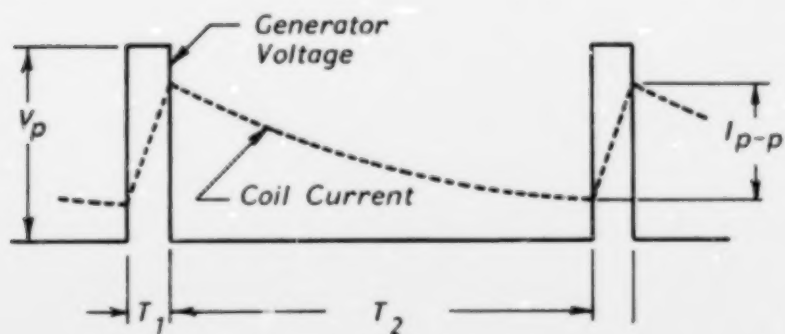
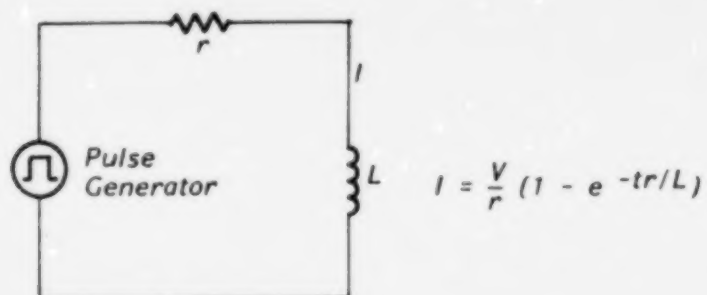


FIGURE II.1
SCHEMATIC OF INTEGRATING CIRCUIT

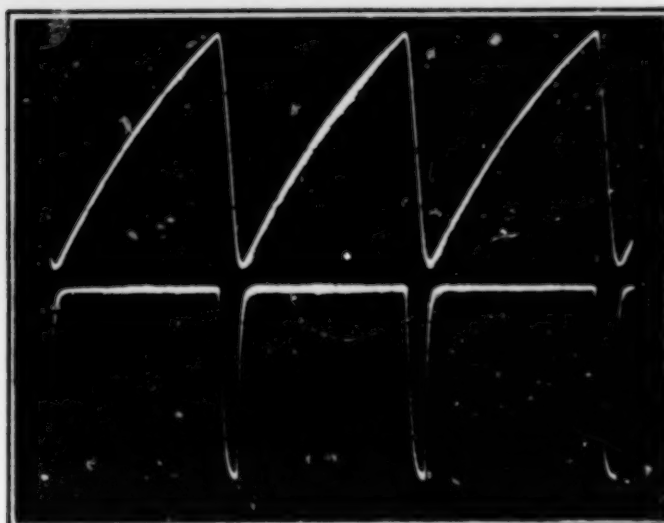


FIGURE II.2
TOP - FIELD AT CENTER OF COIL
BOTTOM - VOLTAGE ACROSS COIL
HORIZONTAL SCALE IS 20 μ s/div

APPENDIX III

ELECTRICAL DESIGN CRITERIA: 60 Hz FIELDS

Electrical design criteria for operation at 60 Hz will depend on the number of turns selected for the VDU experiment. The following calculations are based on a selection of $N=4$. Other values of N will vary the ratio of V to I but will leave the VA rating and total amount of copper the same. The recommended coil will have an inductance of about 100 H and an inductive reactance at 60 Hz of 0.038 ohms. To prevent excessive heat dissipation, an additional constraint is imposed that the resistance should not exceed the inductive reactance. The minimum copper cross section may then be calculated from the linear length of the windings which for the recommended coil is about 40 m.

It can readily be shown that for a magnetic field at the center of the coil of 1 mT rms, the required current is 176 A rms, and the voltage is 9.4 V rms. The volt-amp rating is 1650 VA and the heat dissipation is about 1200 W which, at a water flow of 1 gallon/minute, will raise the temperature of the water by 4°C. The minimum conductor size is 0.2 cm² corresponding to AWG #4.

The electrical parameters will require a step down transformer and/or a variac for adjusting the field. The closest step-down isolating transformer supplied by Hammond Manufacturing Co. of Guelph is a 120 V/12 V, 2 kVA unit. An electrical circuit of 2 kVA rating will be required in the laboratory.

While a current of up to 176 A rms does not present any particular technical difficulty, it may be undesirable for two reasons. First, quite heavy hookup wire will be required between the power source and the coils. Second, mechanical forces between coil windings may produce detectable sound or vibration.

The 60-Hz current requirement can be reduced by using different coil windings for the high-frequency and low-frequency experiments. An alternative possibility is to use two electrically independent but identical windings of $N/2$ turns each in each half of the Helmholtz coil. The electrical characteristics of the coil could then be varied by connecting the four windings in either series or cross-parallel configuration.

An added feature of split windings is that they can be connected in opposition so that a current may be passed through the coil without producing any field. If sound and vibration can not be eliminated, then this arrangement can be used to provide similar levels at both the exposed and sham-exposed groups, and will help to prevent inadvertent identification of the groups by laboratory personnel.

This possibility has not been examined in detail and may require a re-evaluation of coil design specifications if implemented.